The Physics of Tall Building Collapse

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All Things Related To Earthquakes

PhD from Caltech in Geophysics

16 years with USGS

Joint Prof. in Geophysics and Civil Engineering since 1995

Brad Aagaard, Georgia Cua, Anna Olsen, Masumi Yamada,

Shiyan Song, Kenny Buyco, Becky Roh,

John Hall and his students

Summary

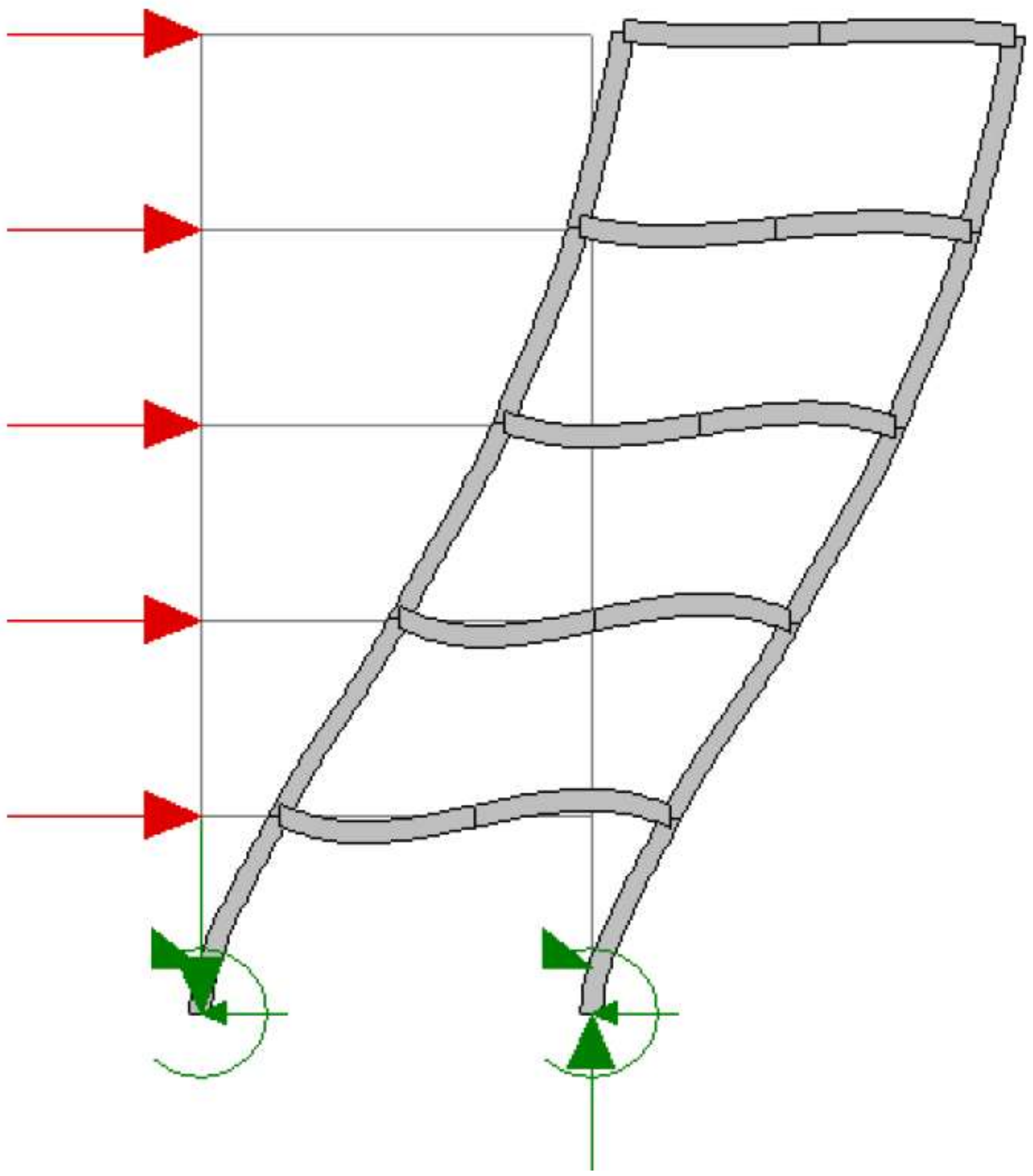
- Peak ground acceleration (pga) characterizes the high-frequency shaking of the ground (> 5 Hz)
- High-frequency ground motions saturate with magnitude and have log-normal statistics. (think heart attacks, murders, etc.)
- High-frequency ground-motion probabilities can be characterized with a rate, a median, and a std. dev.
- Low-frequency ground motion statistics are heavy-tailed power laws (think bird flu, wars, etc.)
- No correlation between near-source pga and low-frequency motions
- In the US, current probabilistic design of tall buildings and base-isolated buildings uses design motions that are smaller than is widely accepted in earth science

Key Issues

- I will concentrate on near-source (less than 10 km from rupture) motions since they are simpler to think about
- Modern high-rise buildings and base-isolated buildings have not yet experienced large long-period ground motions (pgd > 1 m).
- But they will
- Is statistical prediction of long period ground motions technically feasible?
- Maybe … but it will look very different from psha for short periods
- Will the design of long-period buildings change dramatically in the next 100 years?

Flexible or Strong?

- Stiff buildings tend to have high stresses, and must therefore be strong.
- Making a building strong increases the stiffness, which increases the stresses, which increases the required strength of the building (a vicious circle).
- Making a building flexible tends to decrease the stress, but it also decreases the strength of a building (another vicious circle).
- Tall buildings are always designed to be flexible (except in Chile).
- Although there is only one building code, it is very different for flexible buildings.



- Moment-resisting Frame
- Lateral stiffness is mostly from flexure of beams
- Connections between beams and columns must be rigid
- Avoid plastic hinges in columns

Intended yielding is plastic hinges in the beams … avoid yielding in the columns

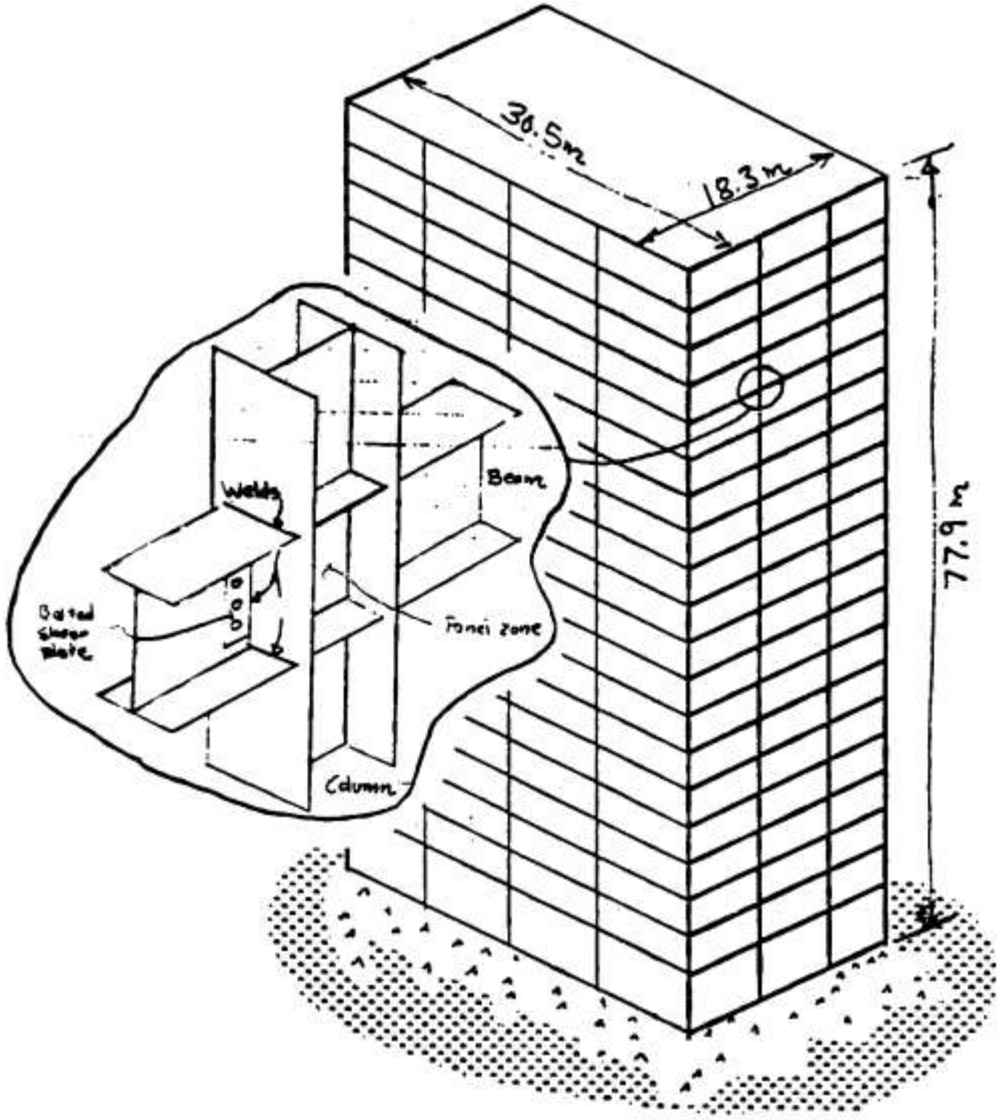
From Chia-Ming Uang UCSD

UNIVERSITY OF CALIFORNIA, SAN DIEGO

Charles Lee Powell Structural Research Laboratories

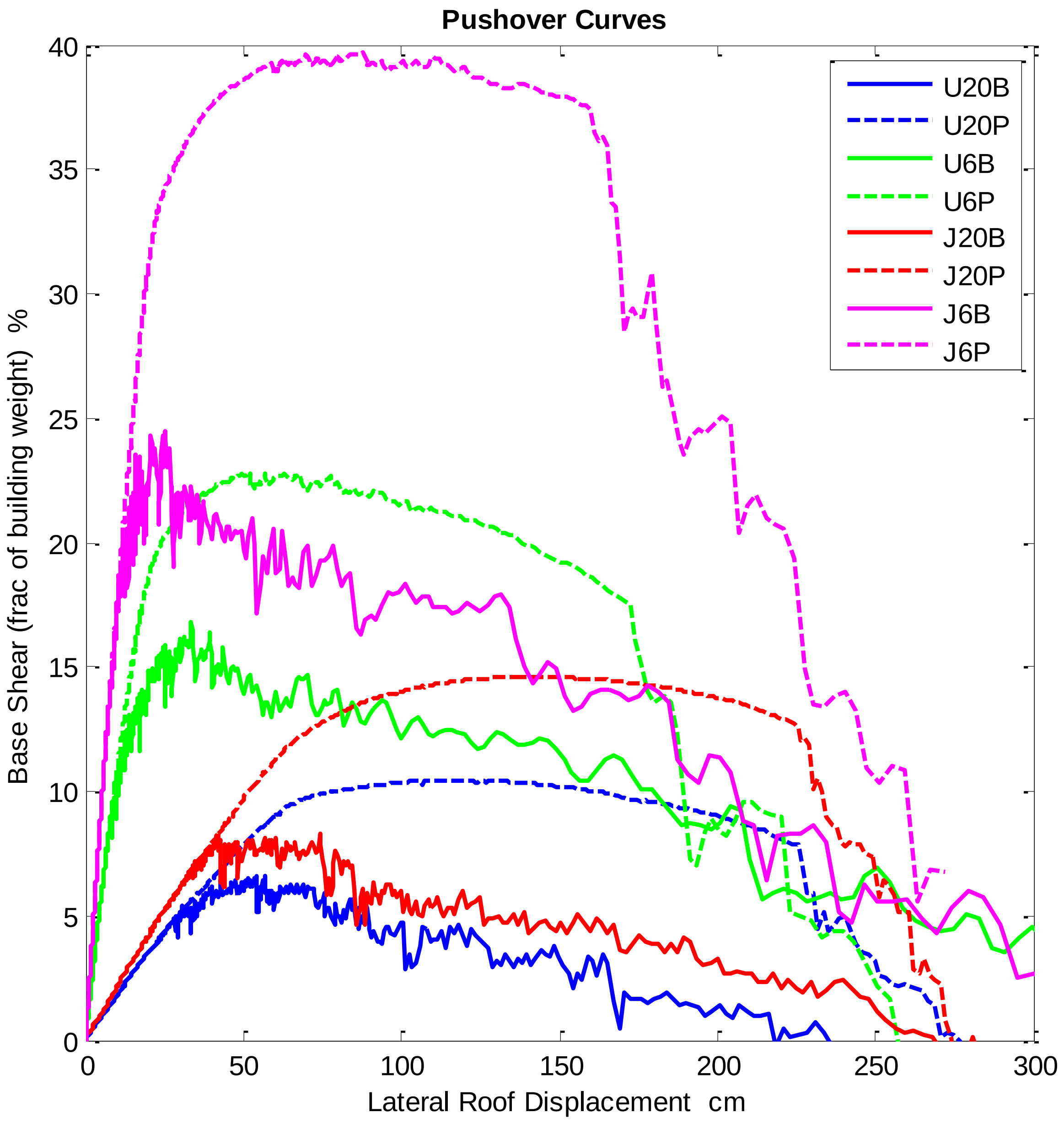
John Hall's design of a 20-story steel MRF building

- •Building U20
  - 1994 UBC zone4 (LA/SF)
  - Stiff soil, 3.5 sec. period
- •Building J20
  - 1992 Japan code
  - 3.05 sec period
  - Similar to current IBC with highest near-source factor
- •Both designs consider
  - Perfect welds
  - Brittle welds
  - Japanese typically exceed code



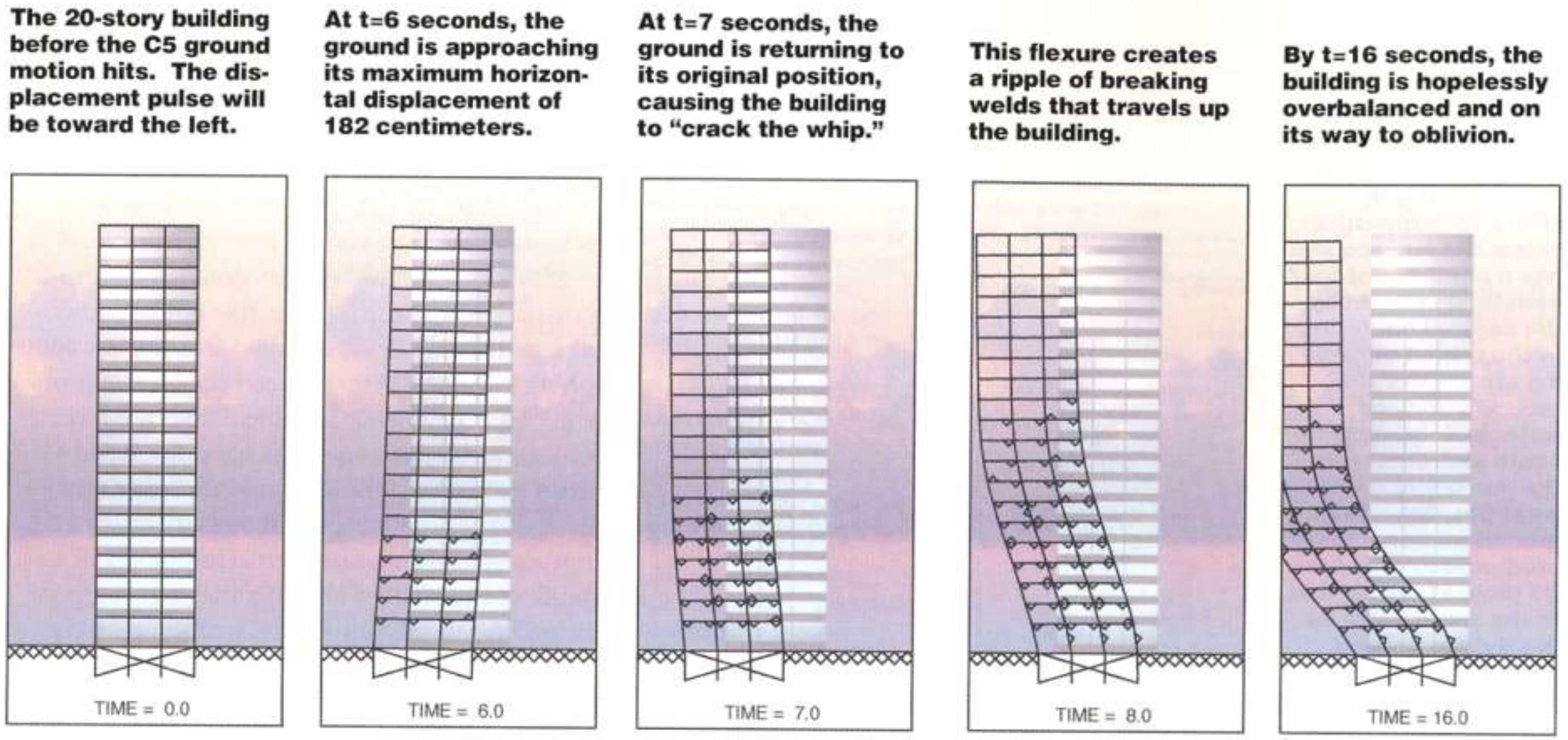
Pushover Analysis

- Special attention to P-delta instability
- Story mechanism collapse
- Frame 2-D fiber-element code of Hall (1997)
- 2 m roof displacement is near the capacity of any of these designs
- Most US buildings built before 1995 have brittle welds

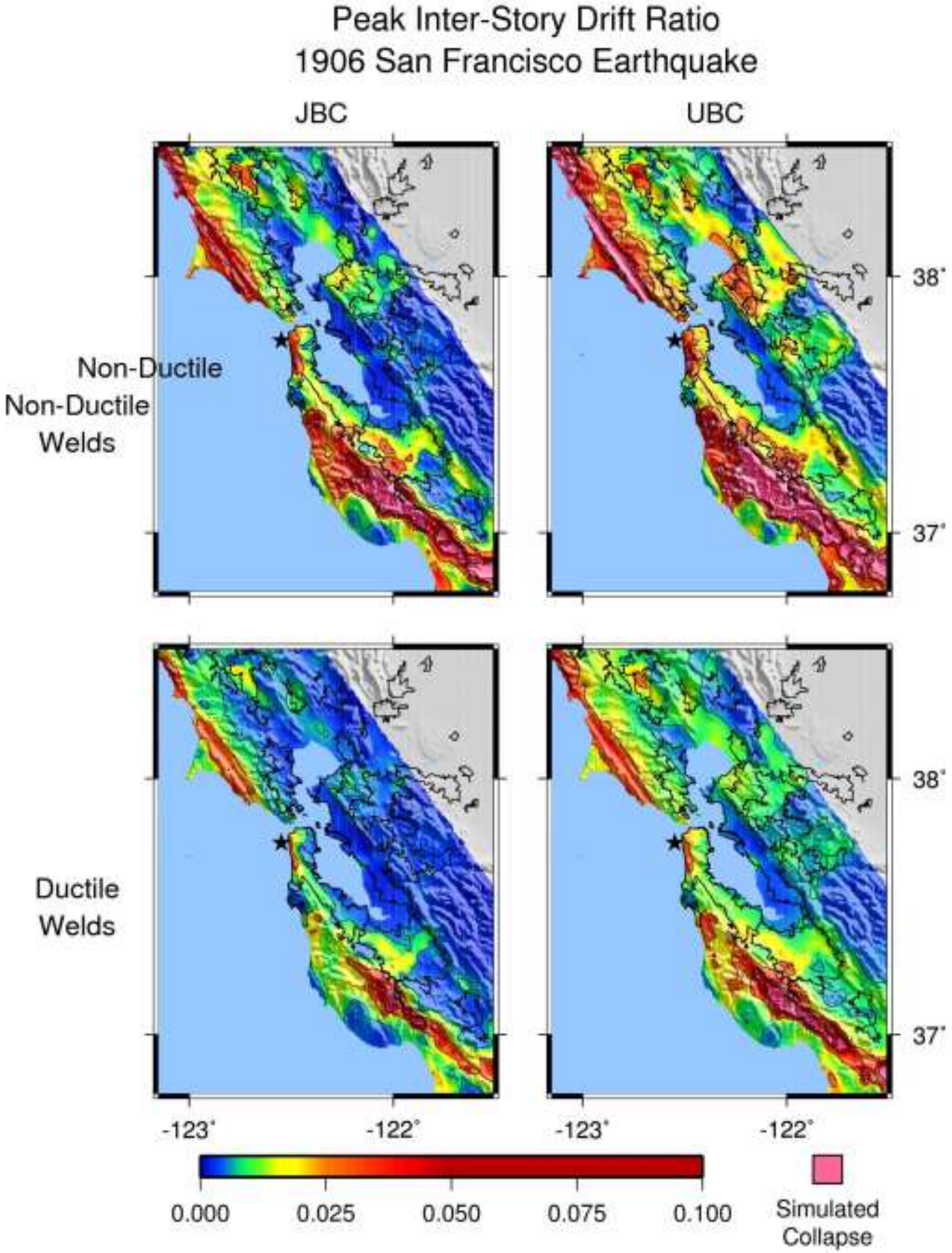


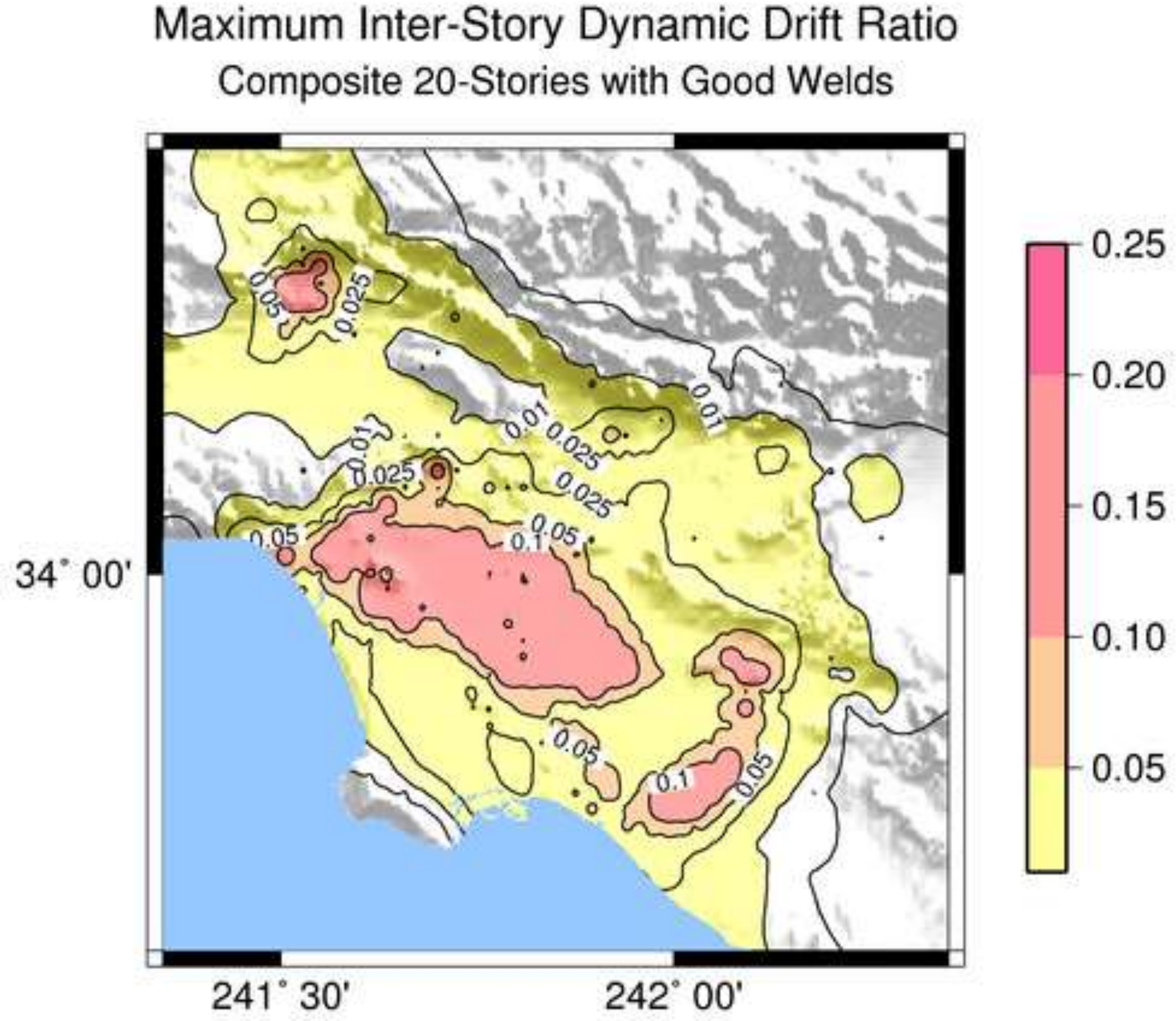
20-story steel-frame building (UBC 94) subjected to a 2-meter near-source displacement pulse (from Hall)

- triangles on the frame indicate the failures of welded column-beam connections (loss of stiffness).



•Results summarized in Olsen, **Aagaard**, and Heaton (BSSA, 2008)
•Severe damage or collapse in many areas
•Stronger, stiffer building (J20) performs better than more flexible building (U20)
•Brittle weld buildings 5 times more likely to collapse than perfect-weld buildings
•Least damage when the epicenter is at Golden Gate
•Would be worse if we simulated soft soils





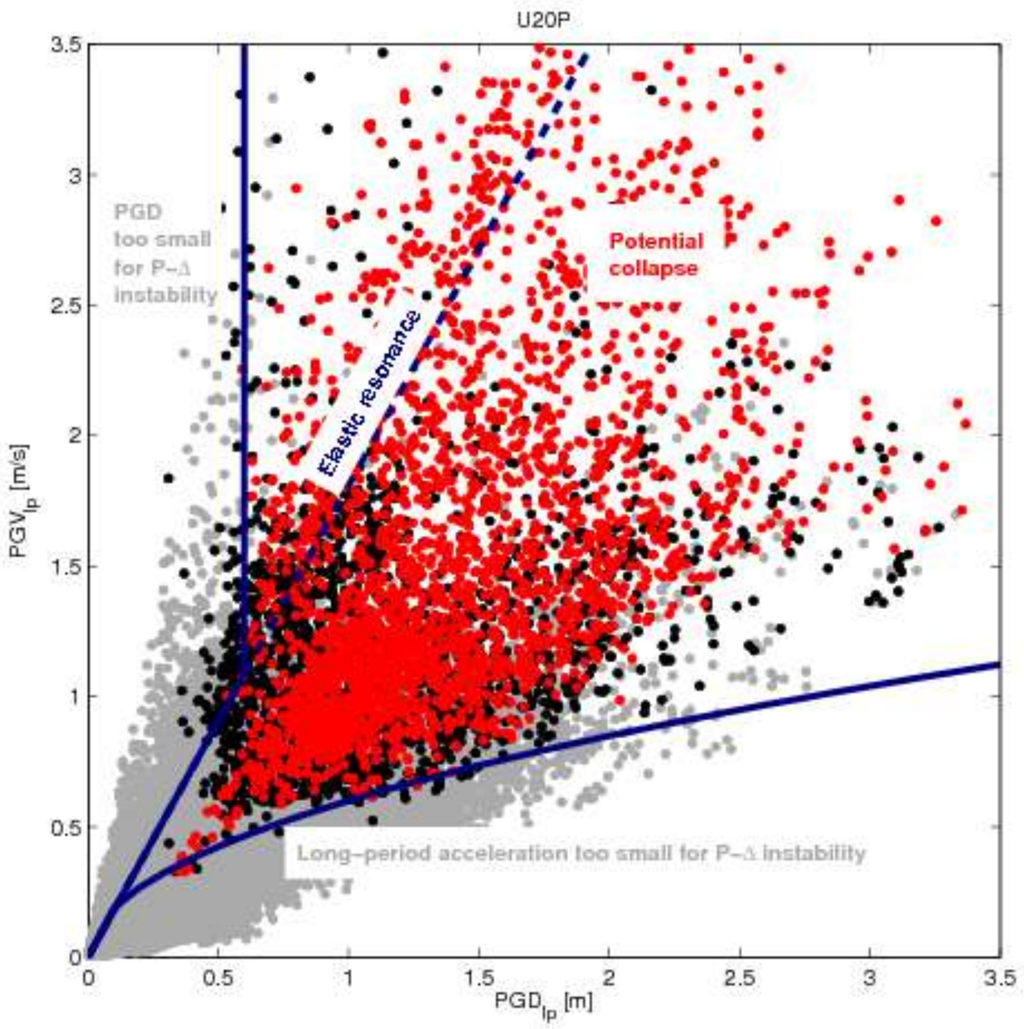
M 7.3 on Puente Hills
Blind Thrust Fault

Motions simulated by Rob Graves

Simulations in Anna Olsen’s thesis

Inter-story drift > 0.8 is collapse

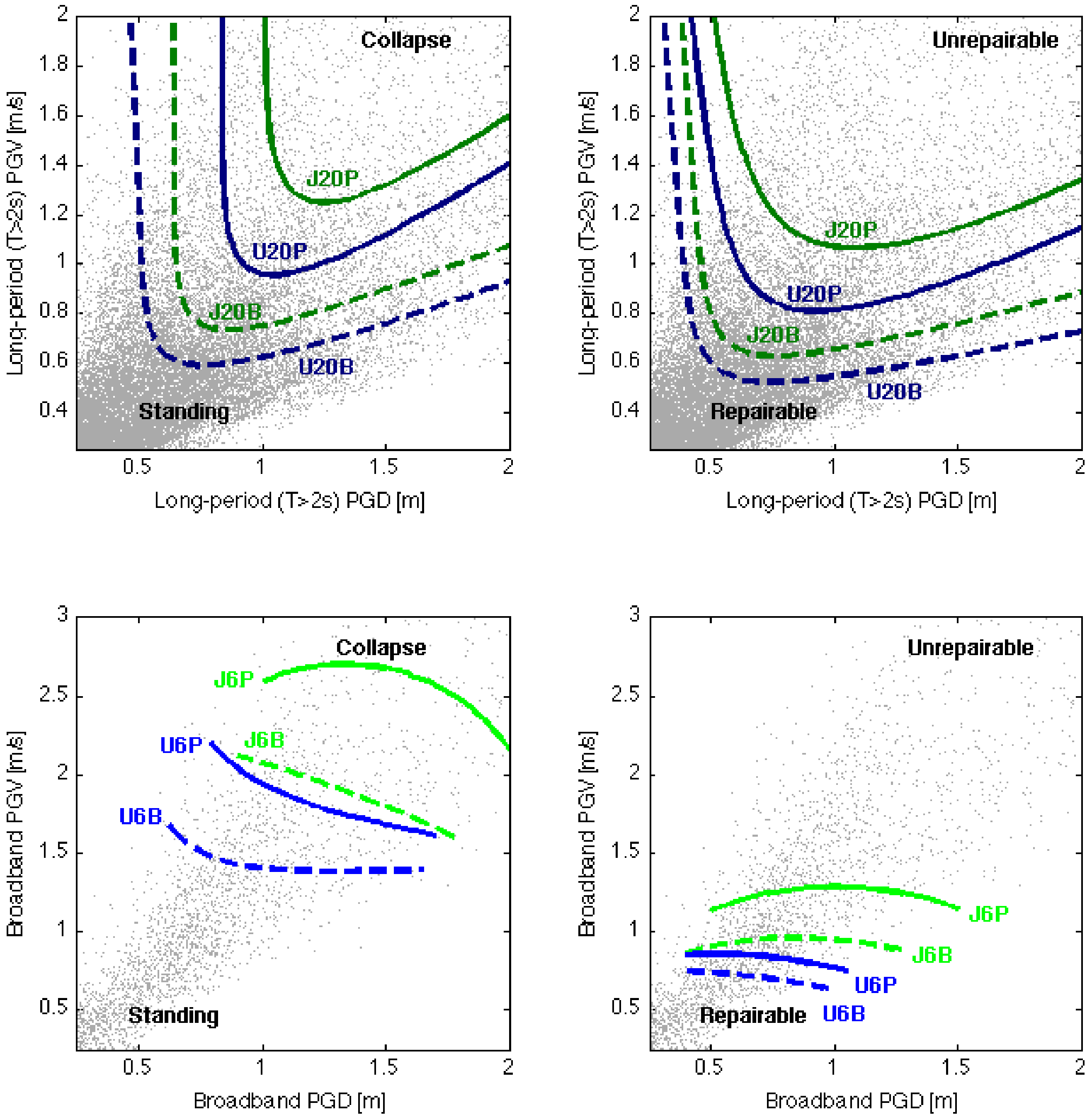
20-story US with Sound Welds



- Repairable
- Not Repairable
- Collapse

Olsen, Heaton, and Hall (Spectra) show that (pgv,pgd) is a better predictor of collapse than response spectral acceleration and ε

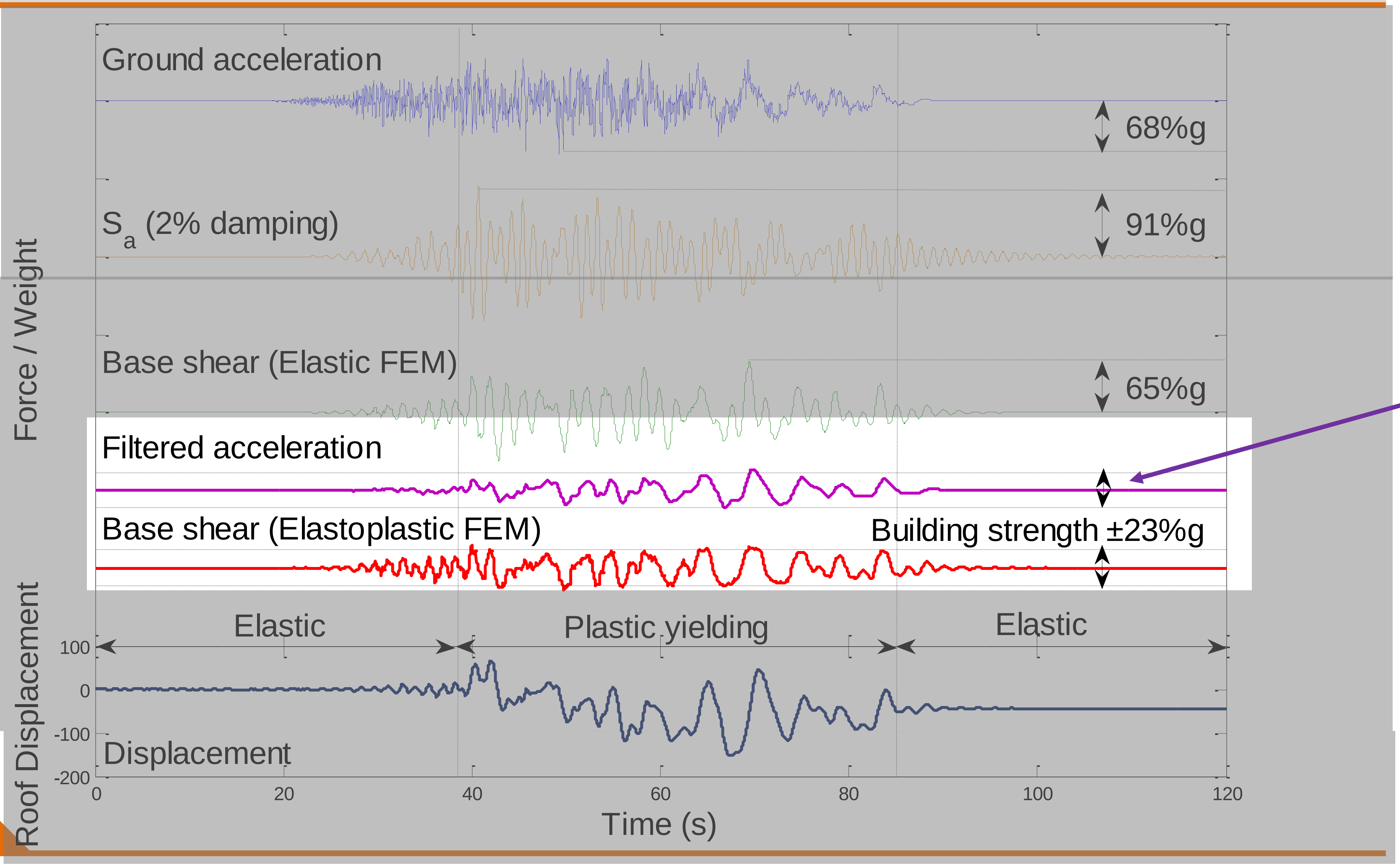
64,000 synthetic records From SCEC



10% probability contours

- Pgv > 1 m/s combined with pgd > 1m is bad
- Range of motions between unrepairable and collapse is much smaller for 20-story than for 6-story
- The **taller building is more brittle** because of P-Δ effect

Filtered Acceleration Characterizes Yielding at Base



Song and Heaton

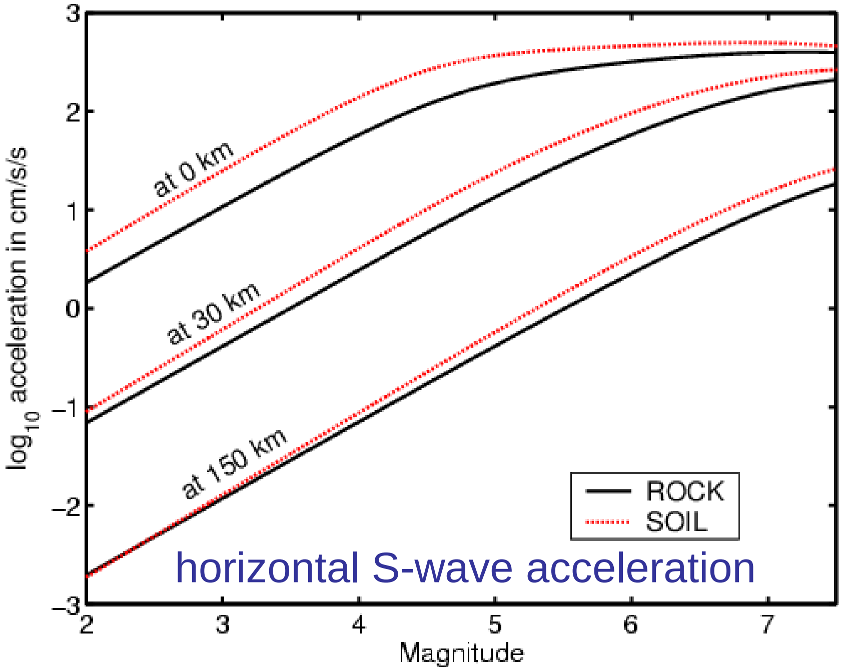
71% damped SDOF
Period = 1.5 x T_0

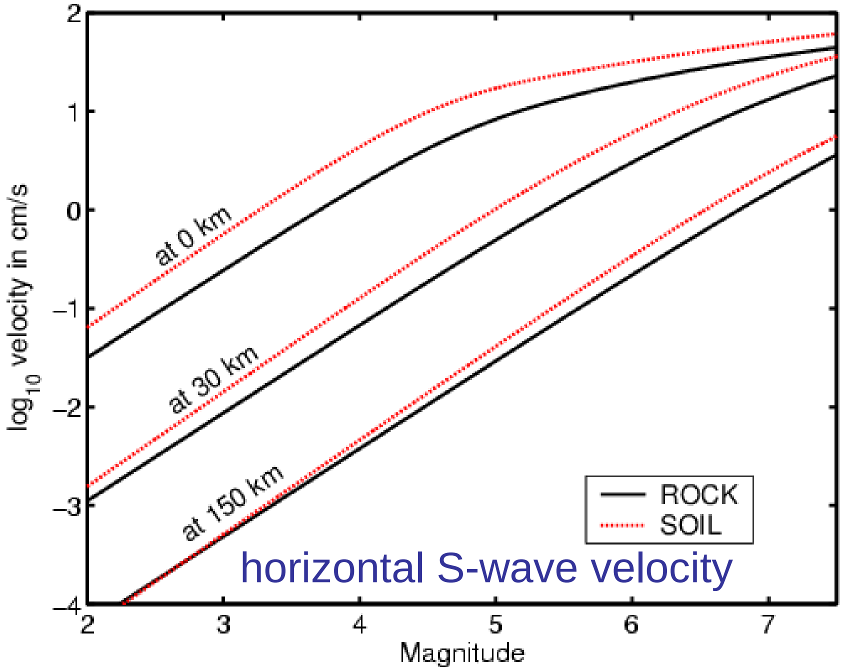
Same as 71% damped SA

Same as a 2-pole Butterworth

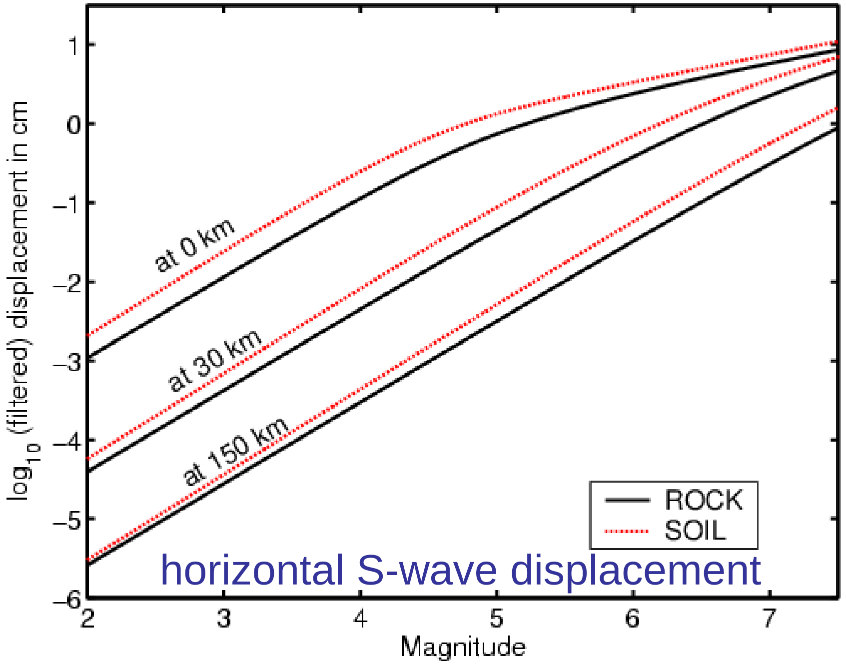
U6P

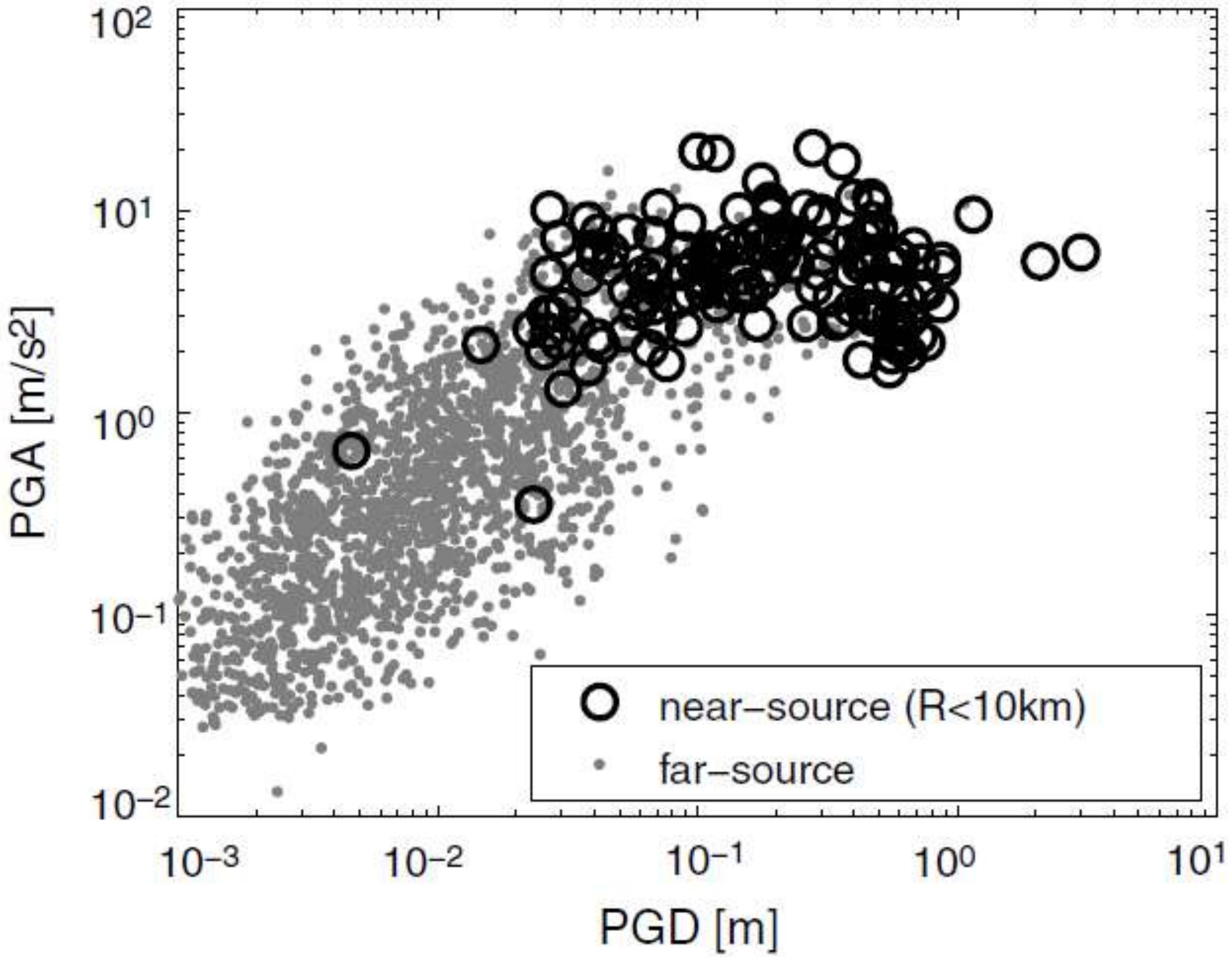
Magnitude-dependent saturation of rock and soil sites (S-waves)





- Ground motion attenuation derived by Cua and Heaton from TriNet and Cosmos data
- For near source motions, high frequencies are log-normally about 0.52 g, regardless of the magnitude and soil type
- Long-period motions do not saturate and the frequency versus size obeys a power law (variation of Gutenberg Richter)
- Log-normal statistics (high frequency hazard) is dominated by the median, whereas power law statistics (long-period hazard) is dominated by the tail



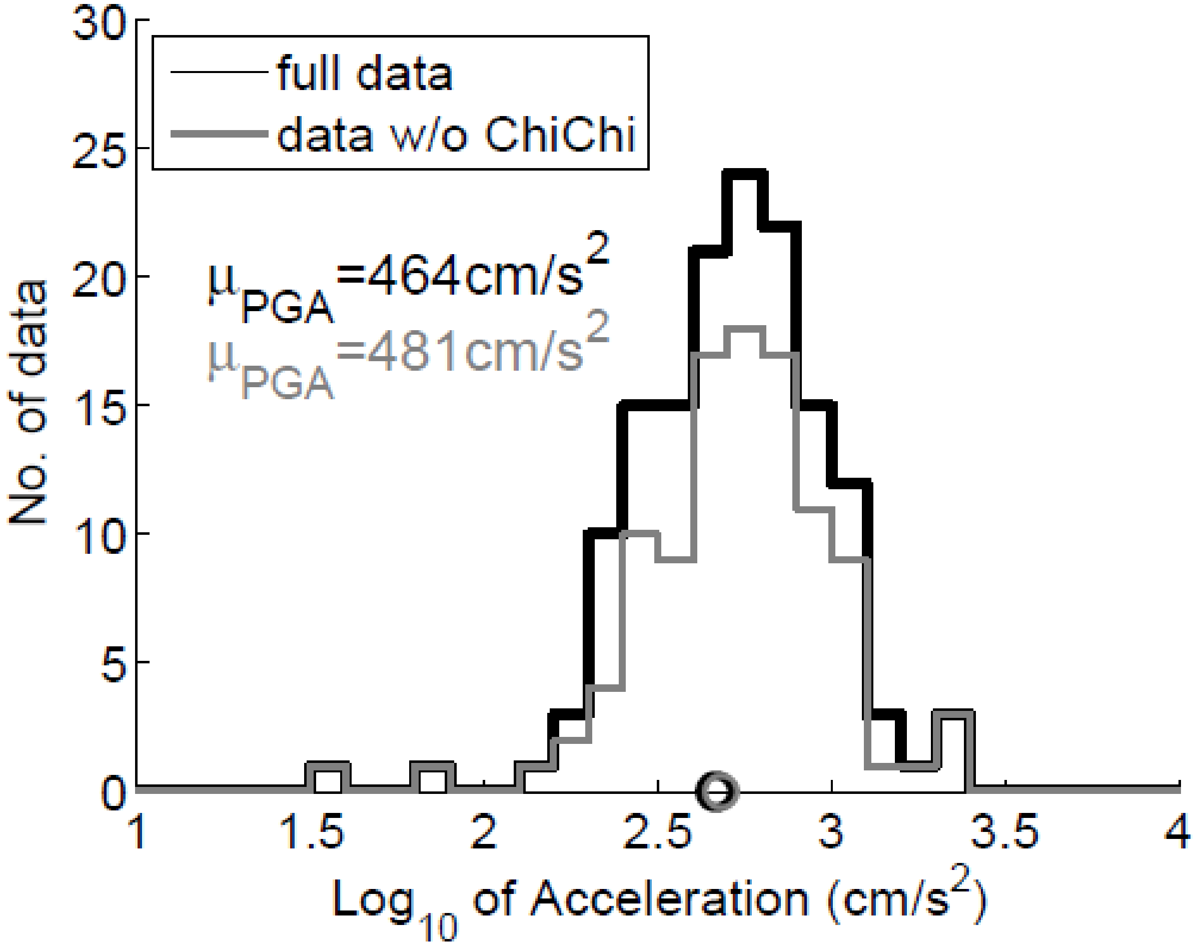


- **near-source pga is uncorrelated with pgd**
- **Pga saturates, but pgd does not**

Yamada, Heaton, and Olsen

All Pga's recorded at less than 10 km from M>6

- Near-source pga's are log-normal
- Same distribution will apply 100 years from now

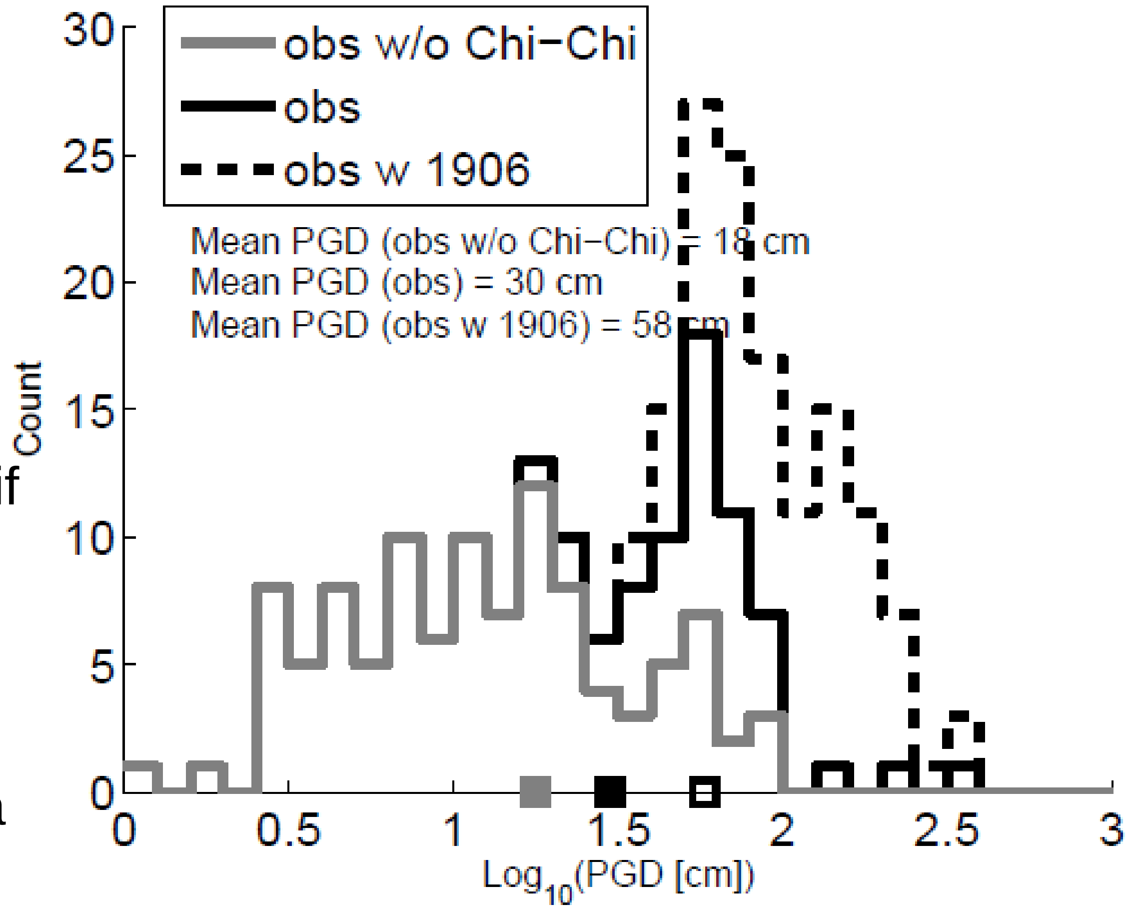


Yamada, Heaton, and Olsen

Short periods are Gaussian statistics

- Can reliably determine the mean and standard deviation from only a few dozen observations
- How many people will die in auto accidents?
- How many people will suffer a heart attack?
- How many buildings will experience some level of pga?
- Although we can predict short-period ground motion statistics, no one really uses them for the design of short buildings … rule based codes function well here.

- Long-period ground motions are **not** log normal
- A few large earthquakes can completely change the distribution
- **Cannot predict** what the shape of this distribution will look like 100 years from now
- Area(M)~$10^{M}10^{-bM}$=constant, if b=1
- i.e., given that a fault slips, **all values of slip are equally likely**
- The small pgd's will come in a few at a time as smaller but numerous eq's occur
- The large pgd's will arrive in a large clump when infrequent large eq's occur

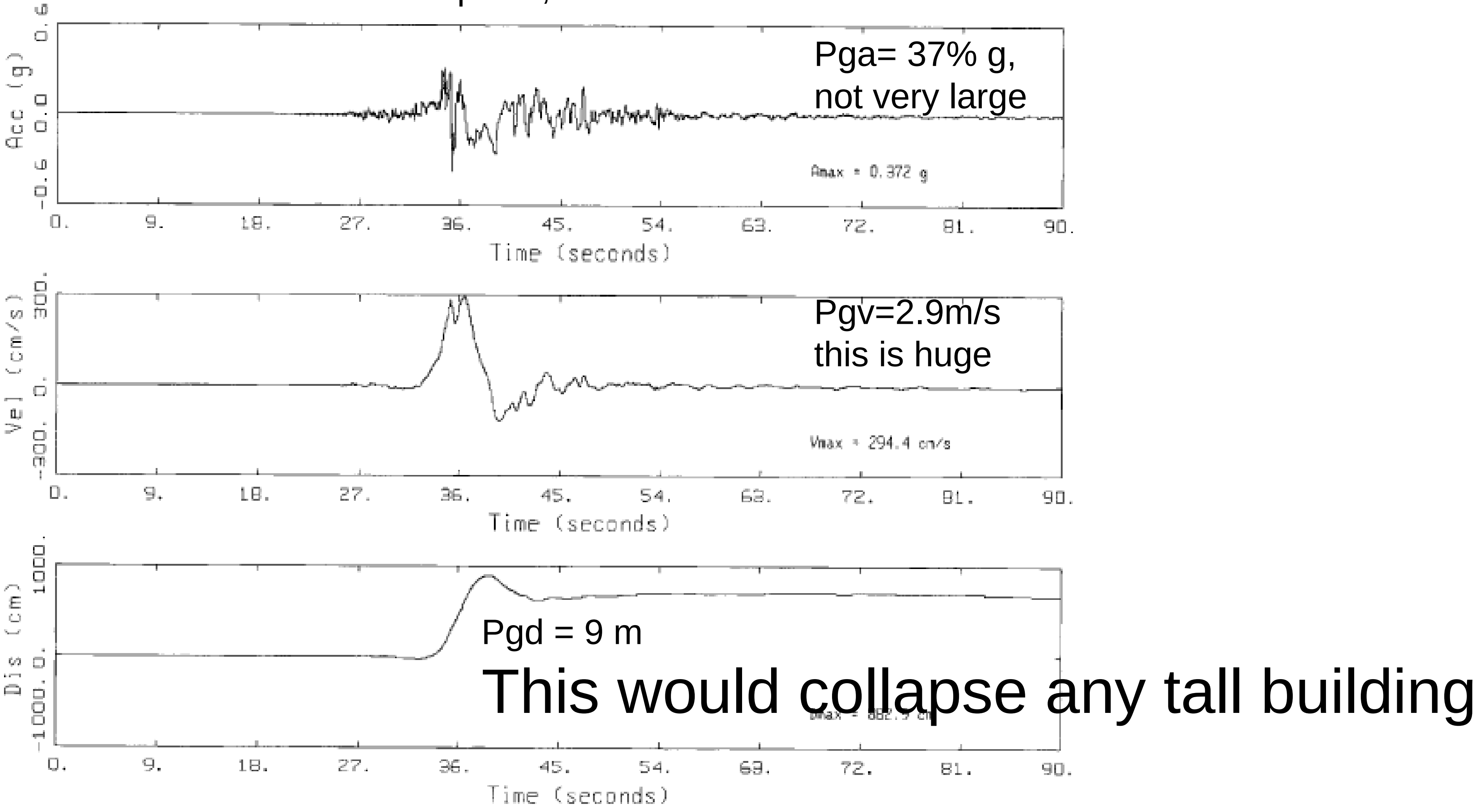


Long Periods are power law statistics aka. a Pareto Distribution

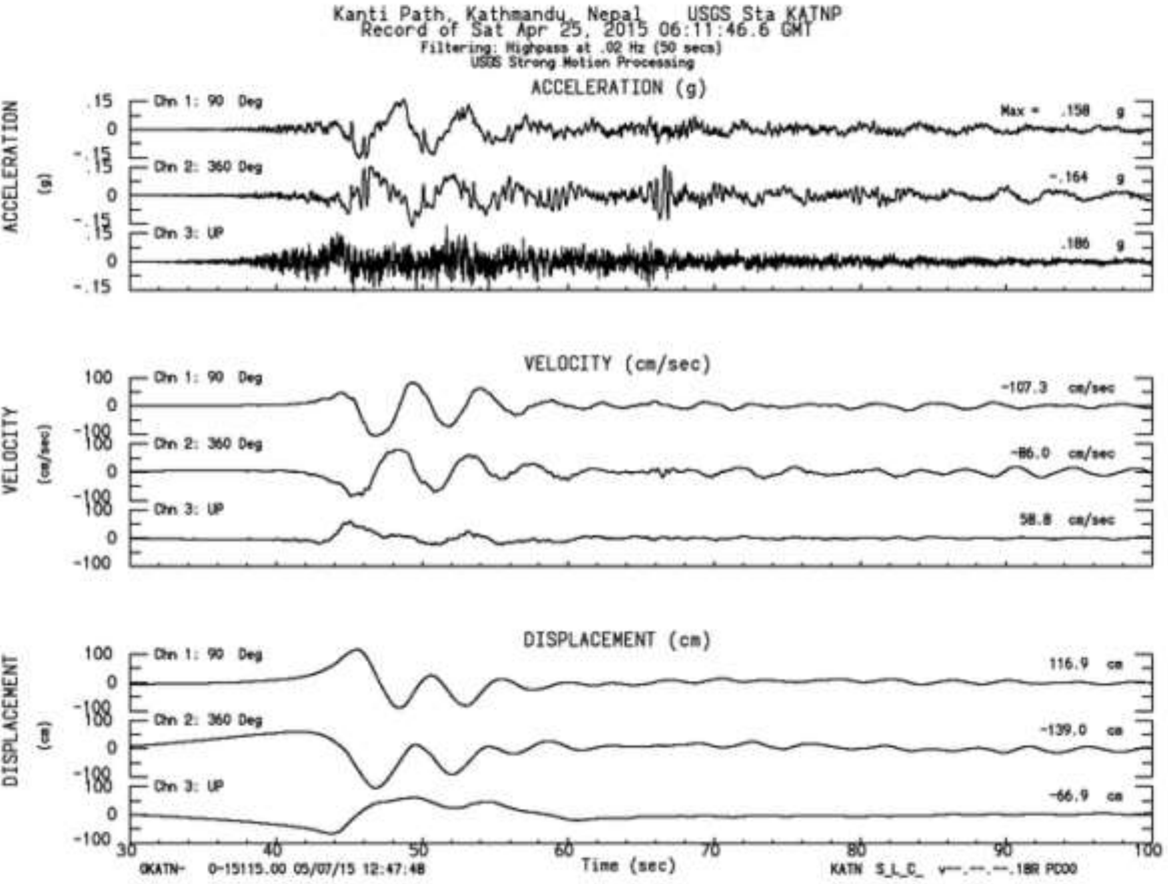
- Probabilities are difficult to estimate for power law. What is the total wealth in California?
- How many people will die in
- A war?
- A pandemic?
- What will your stock market investments look like in 20 years?
- Mean and variance are undefined for many Pareto distributions

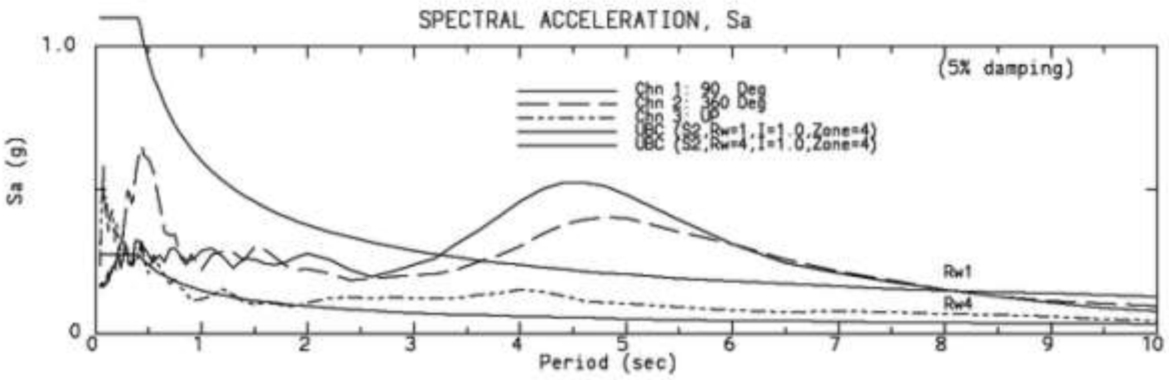
From Silva and Darragh

Chi-Chi Earthquake, M 7.7



CHICHI EQ: TCU068 (NORTH-SOUTH) STATIC TIME HISTORIES





US Club Kathmandu, Nepal

- Pga = 16% g, surprisingly small
- pgv = 107 cm/s very large
- Pgd = 140 cm   HUGE
- ½ g spectral acceleration at 5 s
- Would collapse any skyscraper


04-25-2015 Sat 11:56:18
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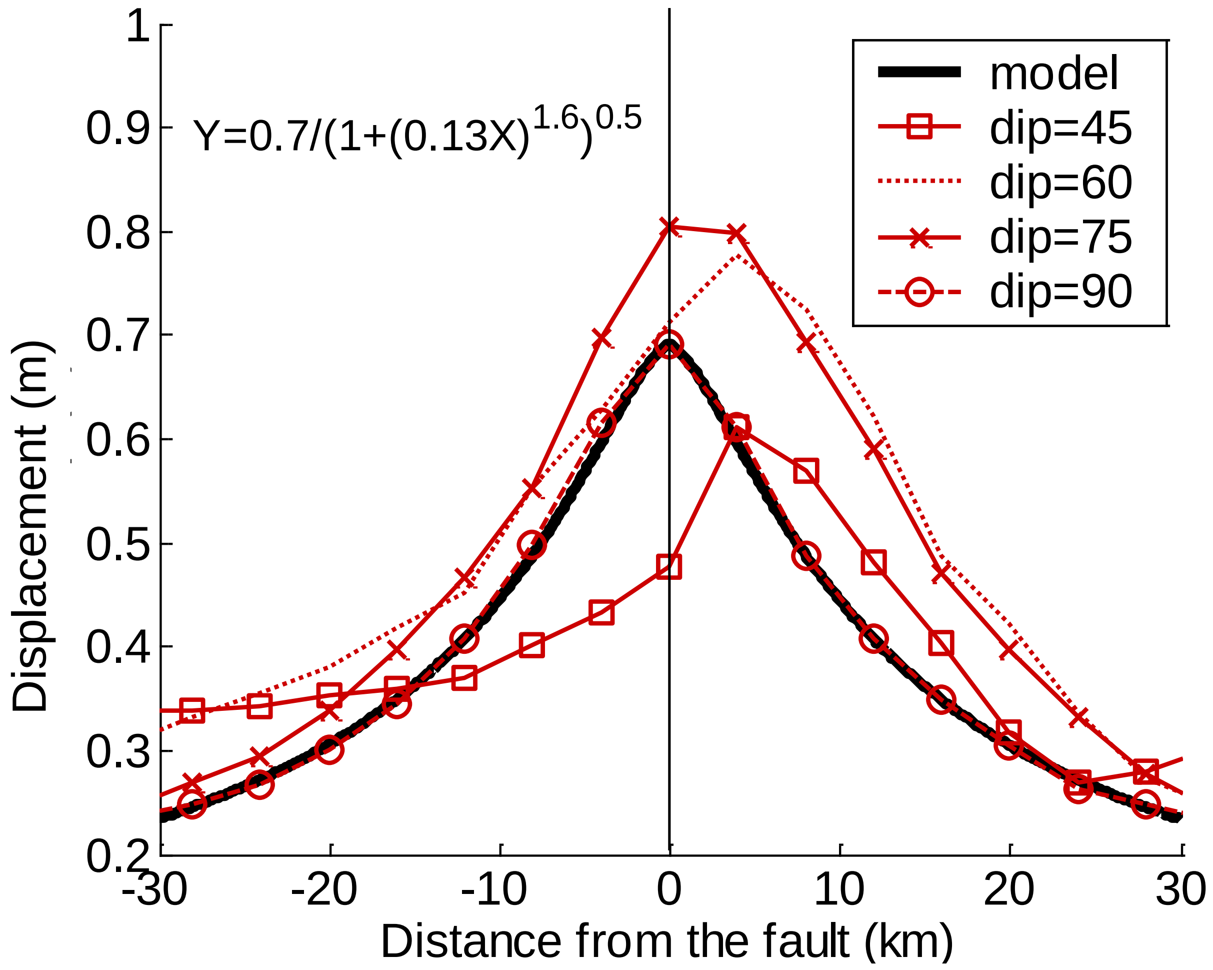
PGD per unit fault slip



(Aagaard et al. 2001)

Near-Source PGD's are roughly **2/3 of the fault slip** in nearby segments.

But what will the fault slip be?

For strike-slip fault,

$$D = \frac{0.7}{\sqrt{1+(0.125r)^{1.55}}}$$

Earthquake magnitude is the wrong parameter

- If you keep everything the same (fault segments, rupture velocities, etc.) and you double the slip, then the long period ground motions double in amplitude (it’s linear)
- If you double the slip, then the magnitude increases by 0.2 units (e.g., a M 7.8 becomes a M 8.0)
- Currently used relations predict that long period motions should only increase by 20%

Centuries of eyewitness observations are ignored

- Numerous mature redwood trees were snapped 10 m from their base in 1906
- Fault slips of at least 18 m were observed in the 1855 Wairarapa, New Zealand earthquake
- Rocks thrown several meters in the 1898 Assam, India earthquake imply pga>1g, pgv>3m/s
- Extensive areas of shattered ground observed in the 1971 San Fernando earthquake
- Hiroo Kanamori likes to say “anything can happen”

Designing for the Known

- Architect chooses the geometry of a design
- Define probability of forces that design will be subjected to
- Determine the size of elements that will satisfy statistical limits
- This is “performance based design”

Designing for the Unknown

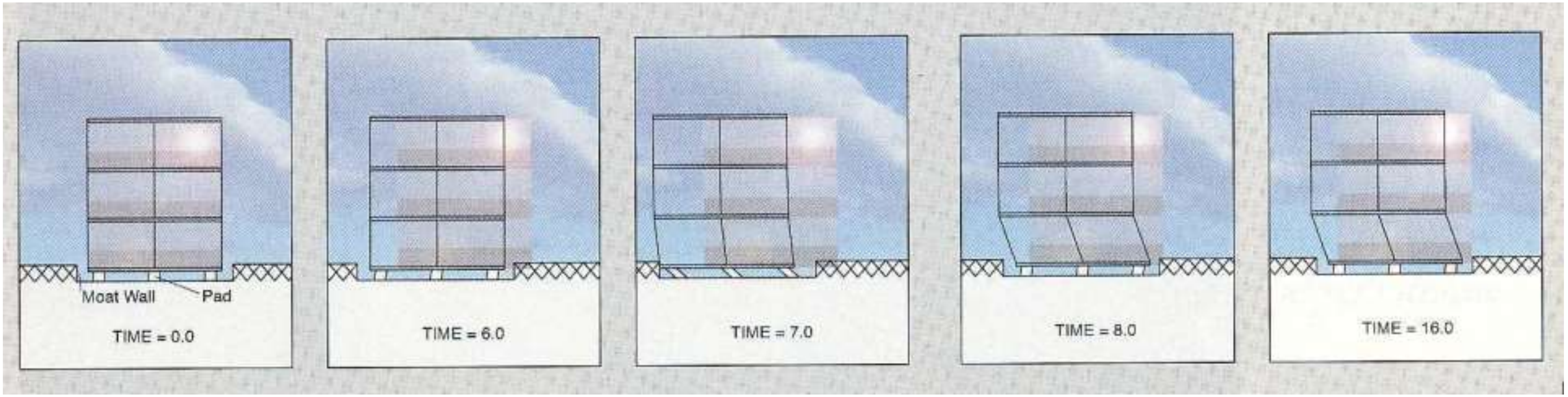
- Determine the functional requirements of a structure
- Consider several geometries of the structure (different architectures)
- Determine the cost of different designs
- Assess the strengths and weaknesses of different designs … **make sure the earth scientist knows what the designer assumes won’t happen**
- Choose the design that is most robust
- Our real job is to find the flaws in current practice and fix them
- Better is ALWAYS better

Some recommendations

- Architects need to understand that their designs constrain the structural behavior of buildings.
- Telling the public that a building is designed for the 2,500-year shaking says that the engineer can compensate for any unreasonable form that an architect can dream up.
- Claim of 2,500 yr design is not a robust scientific conclusion.
- The USGS should not publish NPSHA maps for long-period motions.
- The true answer is, “we don’t know”

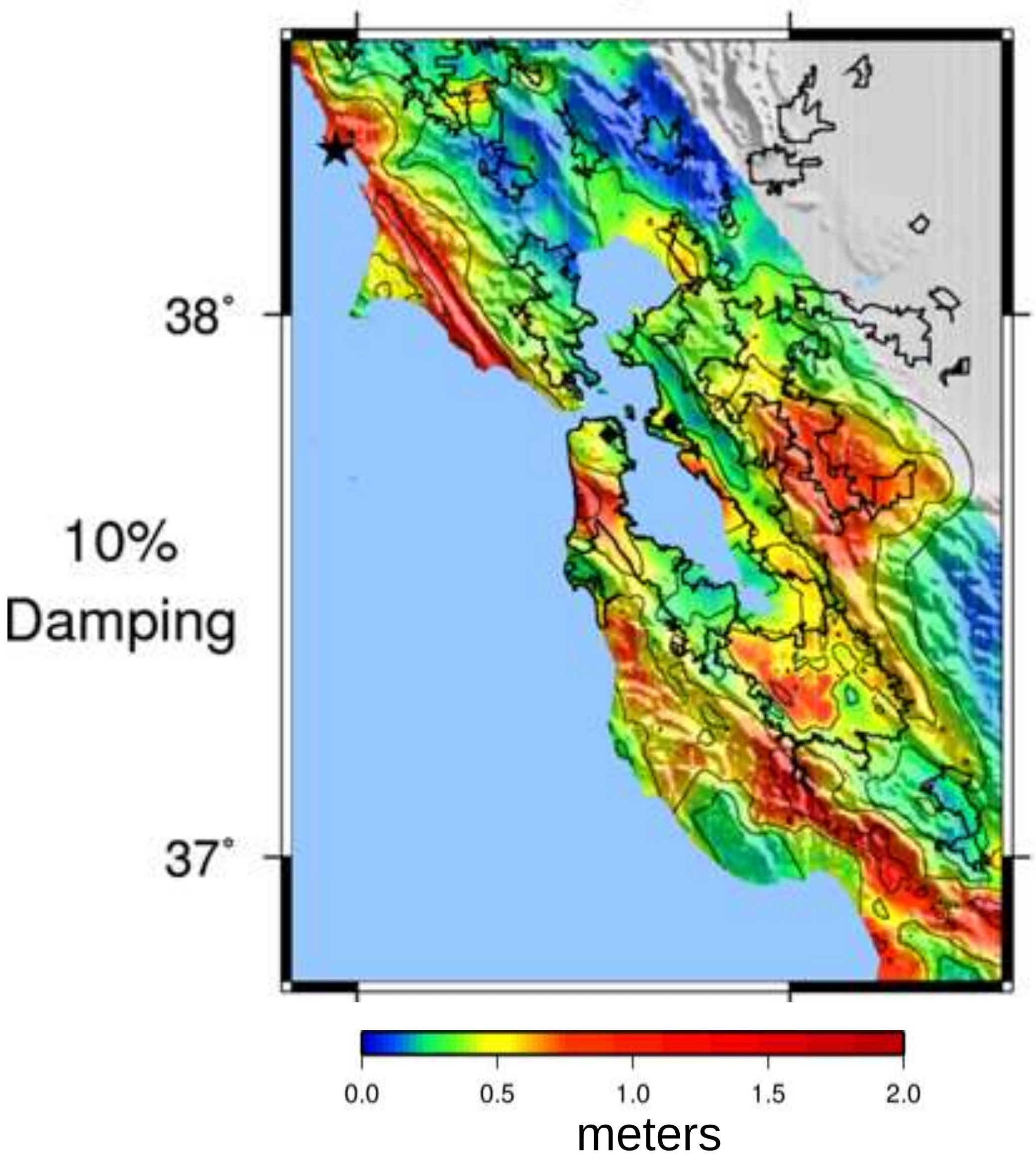
Large displacements can overwhelm base isolation systems

- 2-meter displacement pulse as input for a simulation of the deformation of a 3-story base-isolated building (Hall, Heaton, Wald, and Halling)
- The Sylmar record from the 1994 M 6.7 Northridge earthquake also causes the building to collide with the stops



3-sec spectral displacement

- Typical US base isolator is 3 sec with a maximum allowed displacement of 40 cm
- Nonlinear isolator displacements exceed linear by 20% to 40% (Ryan and Chopra)
- Described in Olsen and others (BSSA, 2008)
- Anything in yellow or red would exceed current typical base isolation system



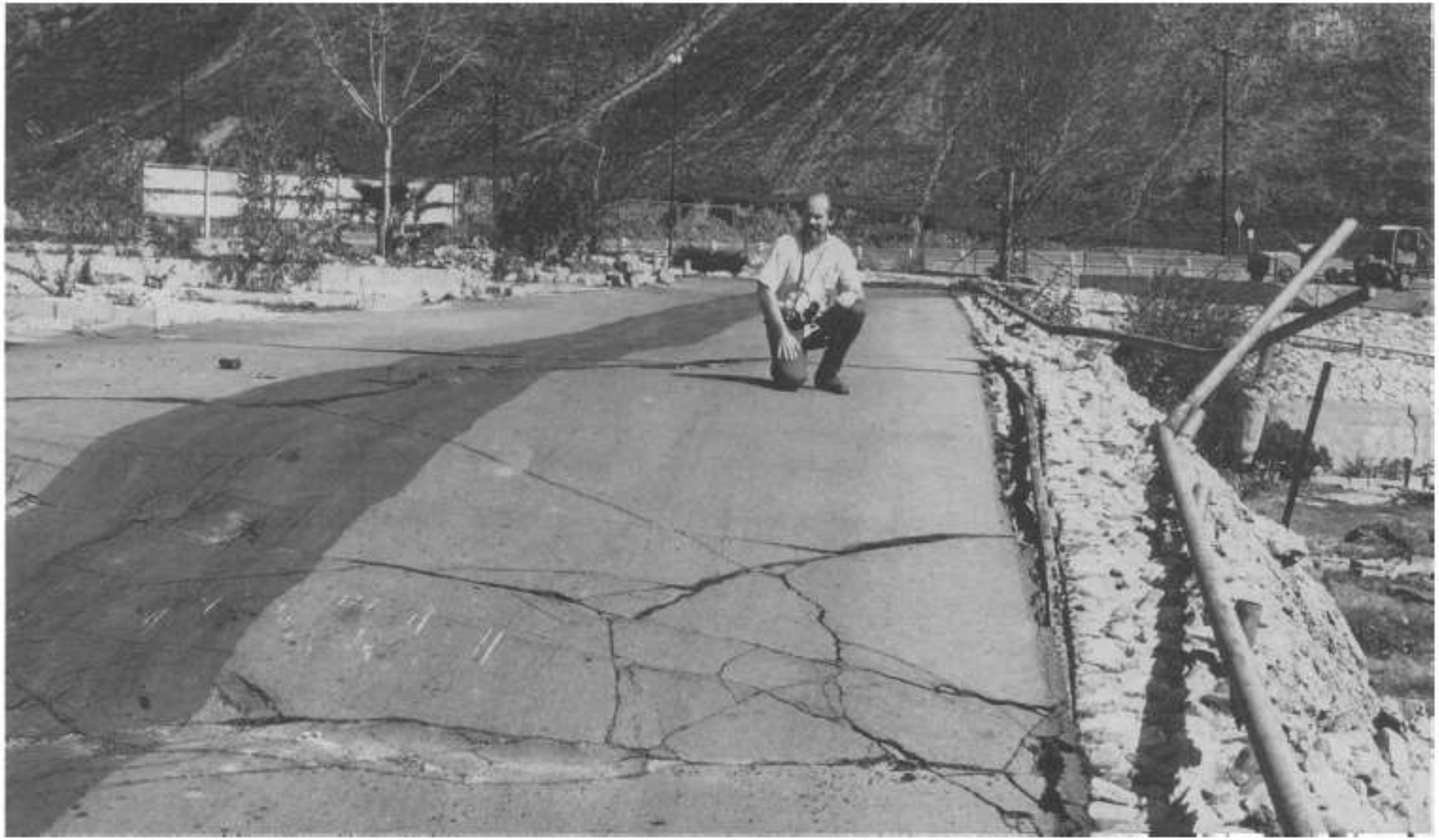
11-story San Bernardino Law and Justice Center

- Triple-pendulum isolators
- 5 ½ s free period
- 1-m maximum displacement
- 6 km from San Andreas
- $400 M construction cost
- Why?????

Why are Earthquakes so Gentle?

- Laboratory tests of fault friction at confining pressure of 10 km depth show friction stress of 200 MPa. (close to the plastic yield stress of structural steel).
- Failure at these stresses is violent (don’t put your fingers near the experiment)
- If earthquakes looked like scaled-up lab experiments, no one would survive an earthquake.

1971 scarp from Brune, Allen, Cluff, Barrows



Railroad tunnel in the M 7.5 1952 Kern County Eq.

FIGURE 5. Damage near the east portal of tunnel 3. Apparently the wall was raised just as the track bent, and the wall then came down on top of the rail. View northwest.

Recent Near-Source records (Buyco, Roh, Heaton)

Earthquake	M	Station	R_{JB}	PGA (g)	PGV (cm/s)	PGD (cm)	Tilt (°)
2016 Kaikōura	7.8	CULC	15.6	0.27	29	75	0.62
		KEKS	3.0	1.97	269	867	1.54
		KIKS	0.7	0.51	160	304	1.83
		WDFS	8.5	2.51	210	816	1.23
		WIGC	18.0*	0.75	64	52	2.73
		WTMC	0.7	1.12	117	284	0.01
2016 Kumamoto	7.0	93048	0.6	0.79	264	186	0.58
		93051	0.5	0.84	178	105	0.48
		KMM001	5.0*	0.22	39	45	0.58
		KMM004	3.9*	0.35	82	74	0.12
		KMM005	5.6	0.54	69	115	0.55
		KMM007	3.5*	0.43	44	40	0.27
		KMM009	2.2*	0.79	38	41	0.19
		KMMH16	0.5	1.18	142	228	0.08
		OIT009	7.8*	0.73	78	102	0.11
2015 Gorkha	7.8	KATNP	0.1	0.16	112	246	0.02
2008 Wenchuan	7.9	AXT	9.8	0.29	31	105	0.04
		MZQ	0.8	0.82	136	213	0.07
		SFB	4.8	0.58	81	318	2.04
2002 Denali	7.9	PS10**	3.0	0.33	137	302	–
1999 Chi-Chi	7.6	TCU052	1.8	0.45	225	740	–
		TCU065	2.5	0.79	135	198	–
		TCU067	1.1	0.50	100	191	–
		TCU068	3.0	0.51	298	885	–
		TCU084	11.4	1.00	118	251	–
1992 Landers	7.3	LUC**	2.0	0.76	146	263	–

* Epicentral distance is reported because R_{JB} is not available.
** Two horizontal directions are oriented parallel and normal to the ruptured fault.